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FLOW VISUALIZATION IN A PARTICLE LADEN JET FLOW

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The results of a flow visualization study of the behavior of an unconfined, steady, fully turbulent, two-phase jet of diameter 12.7 mm at the exit with velocities up to 25 m/s and containing particles with a mass density of loading up to 5% are described. The significant result is the demonstration of "fan spreading", whereby some of the particulates carried by the jet take paths outside of the expected envelope of an equivalent single-phase jet. Measurements of the path angles and a new theory to explain the reason for "fan spreading" is reported.

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1. INTRODUCTION

Proper primer functioning is a prerequisite for uneventful gun operation. Unfortunately, until recently, due to the lack of proper instrumentation some aspects of primer behavior were not known in detail. Lately some excellent progress in our understanding has been made, see for example Chang and Rocchio (1988), but some questions still remain. Overall primers perform satisfactorily, but some facets of the spreading of two-phase jets, which make up many primers, have never been satisfactorily explained. This is of some interest, since the ignition event is considerably enhanced at sites where particles impinge onto the propellant. Thus, particle trajectories are important in the prediction of the ignition process. An interesting aspect of two phase jets is the spreading of particles beyond the expected jet envelope. Accumulating evidence, such as those of Hardalupas et al. (1989), Zoltani and Bicen (1990a) suggests that the observed levels of high fluctuations of the particulate velocity in the streamwise direction in the near field of particle laden two-phase jets are due to "fan-spreading". This is a phenomenon whereby some particles at the exit of a jet take trajectories at angles greater than the expected extent of the carrier jet. Thus particulates can be observed at locations outside of the envelope predicted by single-phase theory. Hardalupas et al. (1989) suggested that this is due to the mechanism that the particles leaving the jet near the edge of the tube are retarded by the tube boundary layer and in addition experience changes in path angle due to turbulent fluctuations inherent in the particulate flow.

Here, we present further evidence, based on flow visualization studies, that indeed the "fan-spreading" takes place in particulate jets. It is also shown that the particles exit the jet with greater angles than those suggested by Hardalupas et al. (1989).

2. THE EXPERIMENTAL SYSTEM

The experimental setup is described in detail in Zoltani and Bicen (1990b). In short, it comprised a jet issuing vertically downward from a pipe of 12.7 mm and laden with 80 μm glass particles at a mass loading of around 5%. The particles showed little response to both the mean flow and turbulence, and exhibit a slip between the two phases of about 25% at the jet exit. Two particle velocities of 25 m/s and 7 m/s at the jet exit were considered. The corresponding velocities of the carrier phase were 32 m/s and 9 m/s respectively.

Flow visualizations were made by means of a CCD camera and a laser sheet having a thickness of around 3 mm at $1/e^2$ intensity level and obtained by a system of lenses from a 20 W copper vapor laser pulsed at a rate of 6 kHz. The CCD camera had a sensitive area of 1024 x 1024 pixels and was triggered by a microcomputer and had an exposure time of about 30 msec. The camera was interfaced with the microcomputer which stored the digital images and performed various filter algorithms to enhance the stored images.

3. RESULTS AND DISCUSSION

The flow visualization images obtained with the higher velocity particle flow are shown in Fig. 1. The mean particle velocity measured by laser Doppler anemometry at the jet axis and near the exit was 25 m/s. The original image, Fig. 1 (a), hardly shows the detailed nature of the particle flow and was therefore enhanced using a high-pass and Sobel filters, see e.g. Gonzales et al. (1987), with the result shown in Fig. 1 (b). It

clearly indicates the individual particles and their tracks. Since the laser was pulsed at 6 kHz, it was also possible to deduce the velocities of individual particles from their signature on the image during the time that the camera shutter was open. The image indicates that the particles exit the jet at various angles and follow straight trajectories with almost constant velocities. There is no evidence of any response of the particles to the turbulent flow field. The exit angles lie within a sector of ± 30° from the jet axis and the velocities associated with particles of large path angles are constantly lower (up to 50%) than the mean particle velocity of 25 m/s. The observed angles are considerably higher than those calculated by Hardalupas et al. (1989) based on the premise that the particles exit the jet at an angle expressed as $\tan^{-1}(v_p/U_p)$ where v_p is the rms of particle velocity fluctuations in the radial direction and U_p is their mean streamwise velocity. Typically, $v_p \cong 0.1\ U_p$.

A plausible explanation for the large angles is the following. Some particles enter the jet tube from the plenum chamber at an angle and bounce off the wall during their transit inside the tube, experiencing different velocities as they do so across the tube. By the time these particles reach the exit they will resume different exit angles and velocities in a random fashion. Their velocities can thus be expected to be lower than those traveling straight through the tube or those experiencing fewer bounces during their transit. It can, therefore, be anticipated that lower jet velocities and lower levels of turbulence will lead to reduced entry angles to the jet tube and consequently to lowered jet exit angles of particles. This is evident in Figs. 2a and 2b which shows a smaller angle of spread and deviation in velocities (up to 15 %) from the measured mean particle velocity of 7 m/s.

A study of the far field of the jet is shown in Figs. 3 and 4. The camera was located

at 1.8 m from the observed plane of the flow. At 5% loading and with a mean exit velocity of 20 m/s, as shown in Figs. 3a and 3b, the integrity and the extent of the jet spreading is clearly discernible. The tracks of the particles participating in "fan spreading" can be followed back to the jet exit.

With the jet exit velocity increased to 25 m/s, the effect of the enclosure on the flow development becomes pronounced. At 40 m/s and 2% loading, as shown in Fig. 4a and b, induced vortex motion in the enclosure is evident. Particles participating in this motion move slower, hence the longer tracks visible to either side of the jet.

4. CONCLUSIONS

Flow visualizations obtained in a two-phase jet flow with 80 μm particles at a mass loading of 5% revealed the following.

1. Particles exited the jet tube in straight trajectories with "fan-spreading" angles of up to ± 30°. The velocities of those particles having large path angles were considerably lower (40 % or more) than the mean velocity of the particle bulk flow.

2. Reducing the mean particle velocity at the exit from 25 m/s to 7 m/s reduced the "fan-spreading" effect with a maximum angle of around 10°.

3. "Fan spreading" may be of significance for the modeling of primer functioning. As we have shown, some of the particles take paths outside of the expected extent of the jet, thus leading to dispersed ignition sites covering an area considerably larger than previously thought possible.

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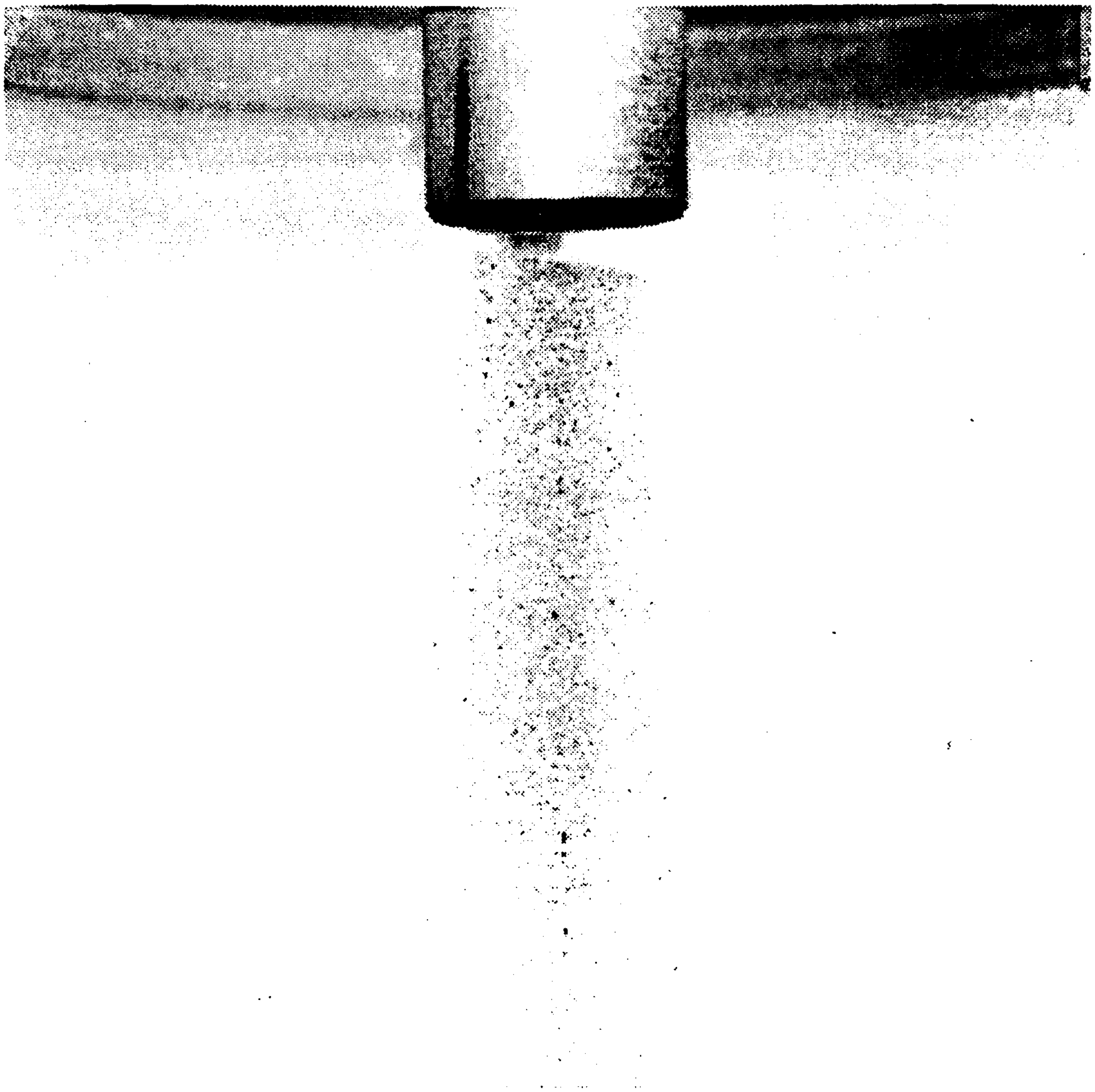

Figure 1. Visualization of high velocity ($U_p = 25$ m/s) particle flow

(a) Original image

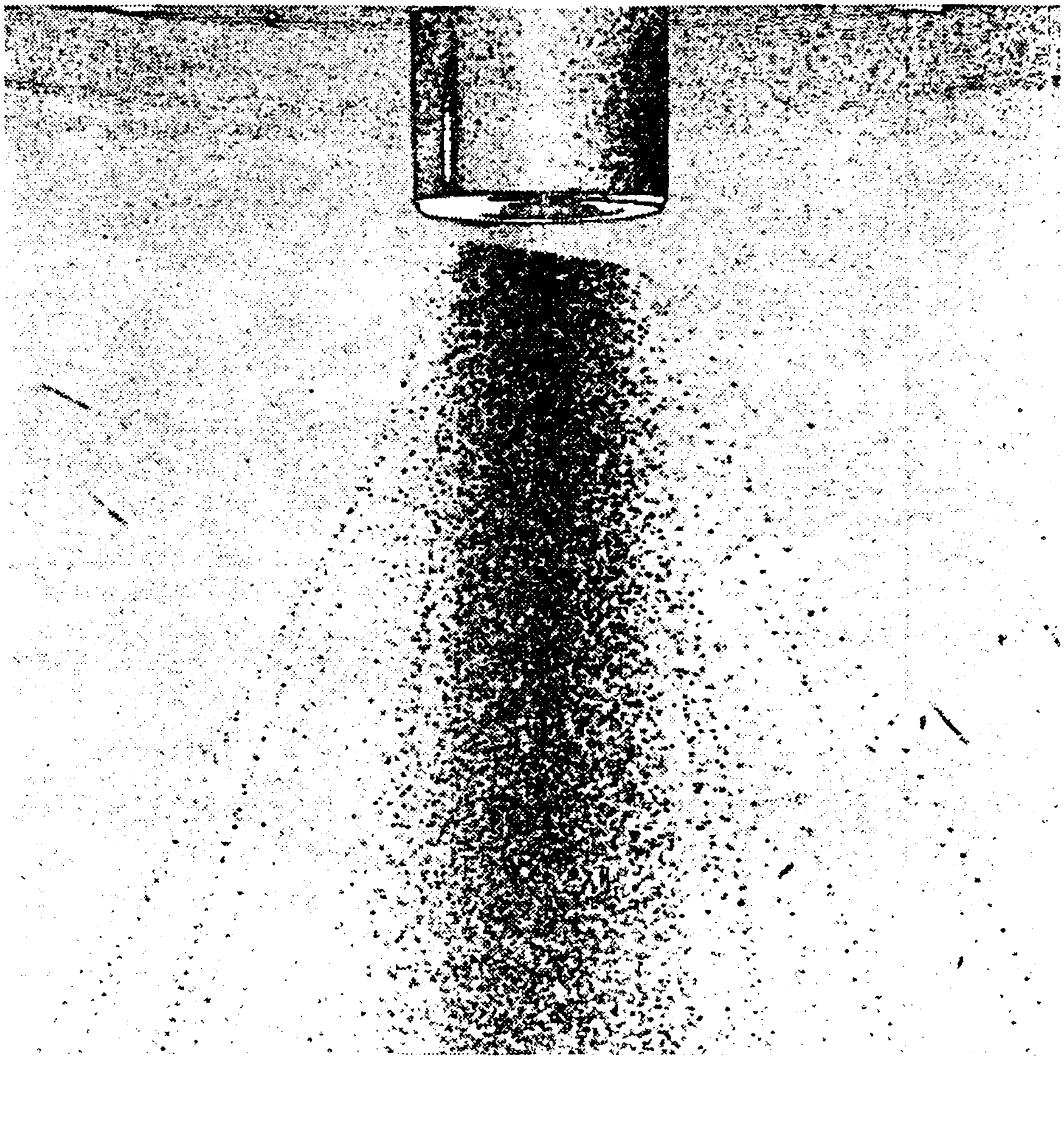

Figure 1. Visualization of high velocity (U_p [illegible] /s) particle flow

(b) Filtered image

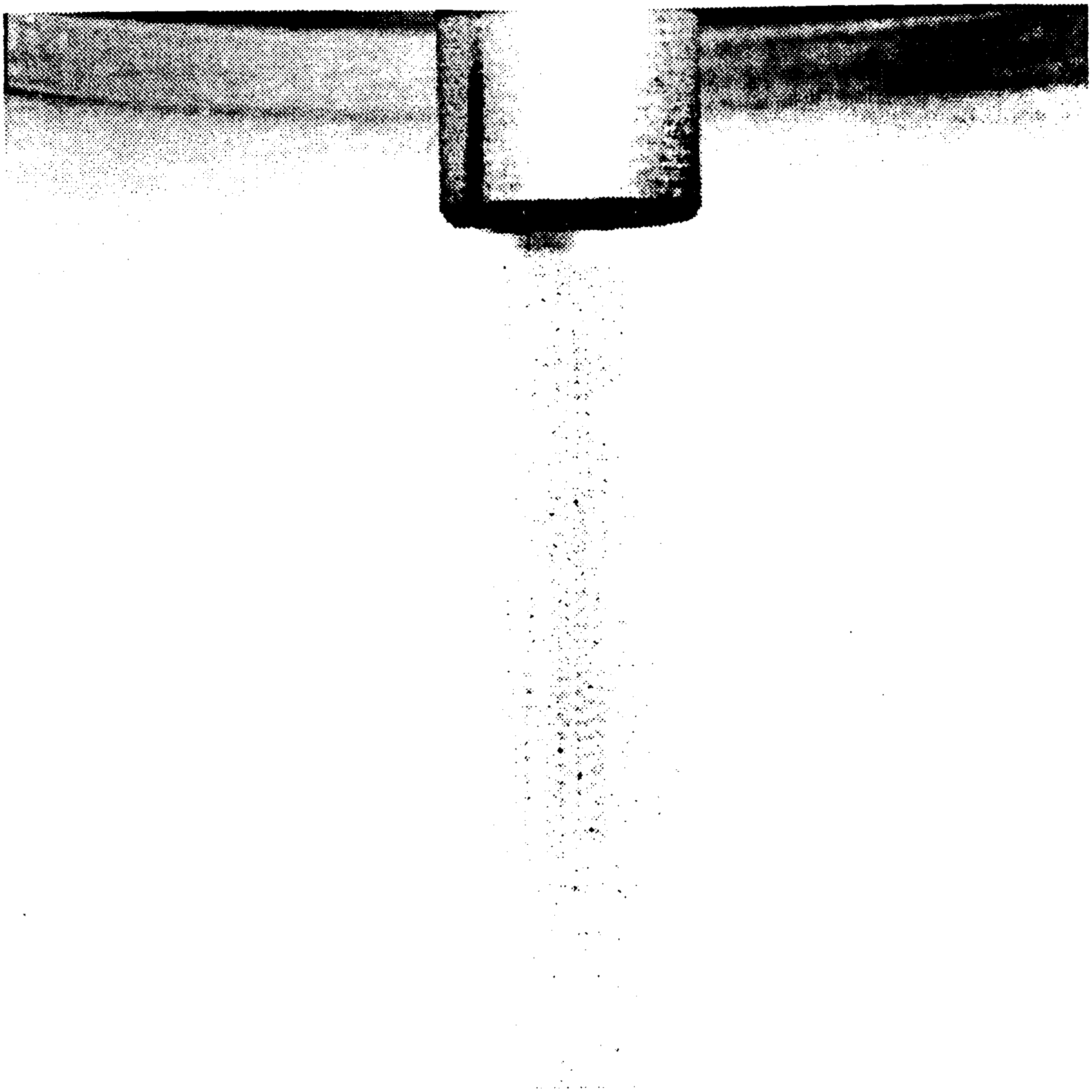

Figure 2. Visualization of low velocity (V_P = 7 m/s) particle flow

(a) Original image

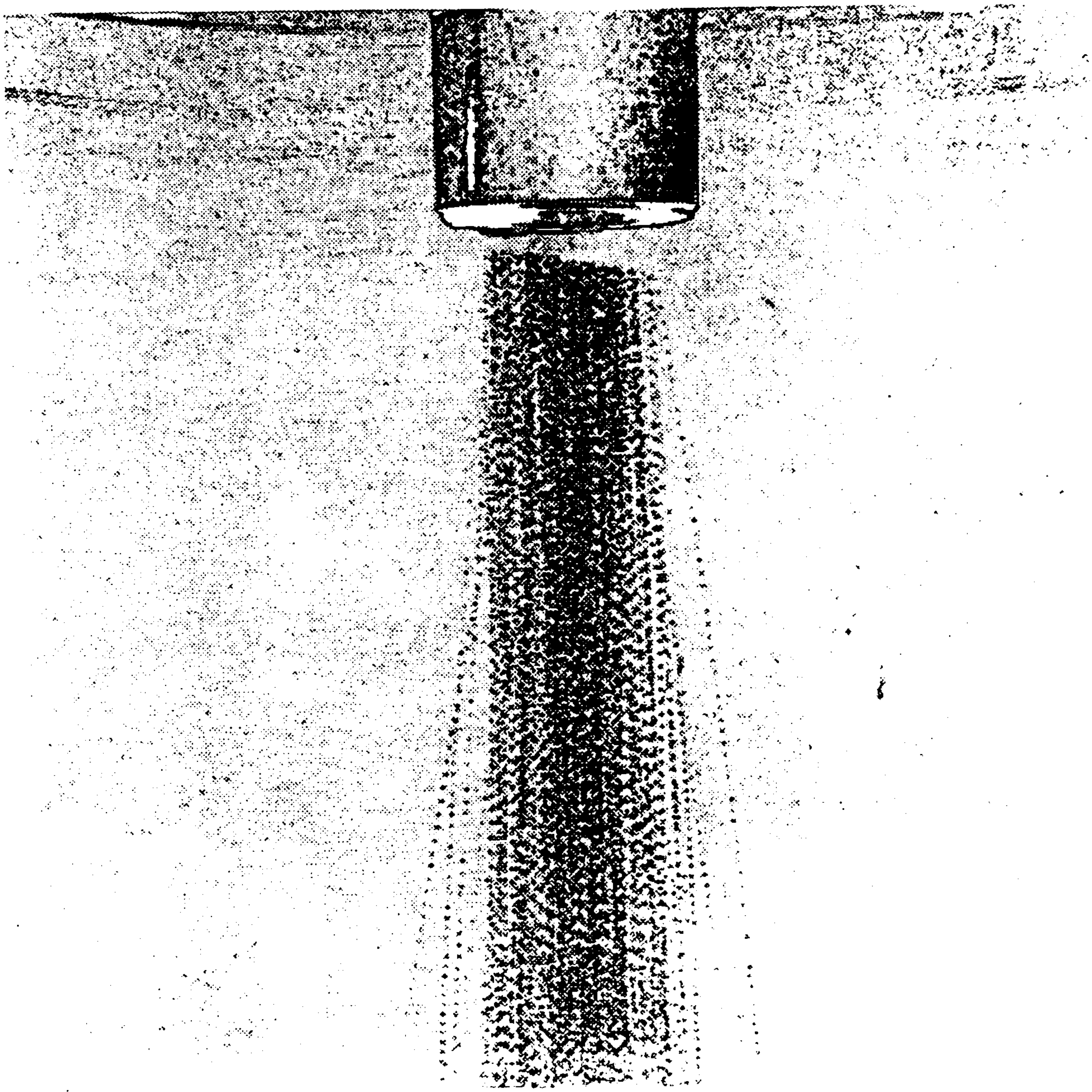

Figure 2. Visualization of low velocity (c_p [illegible]) [illegible]

(b) Filtered image

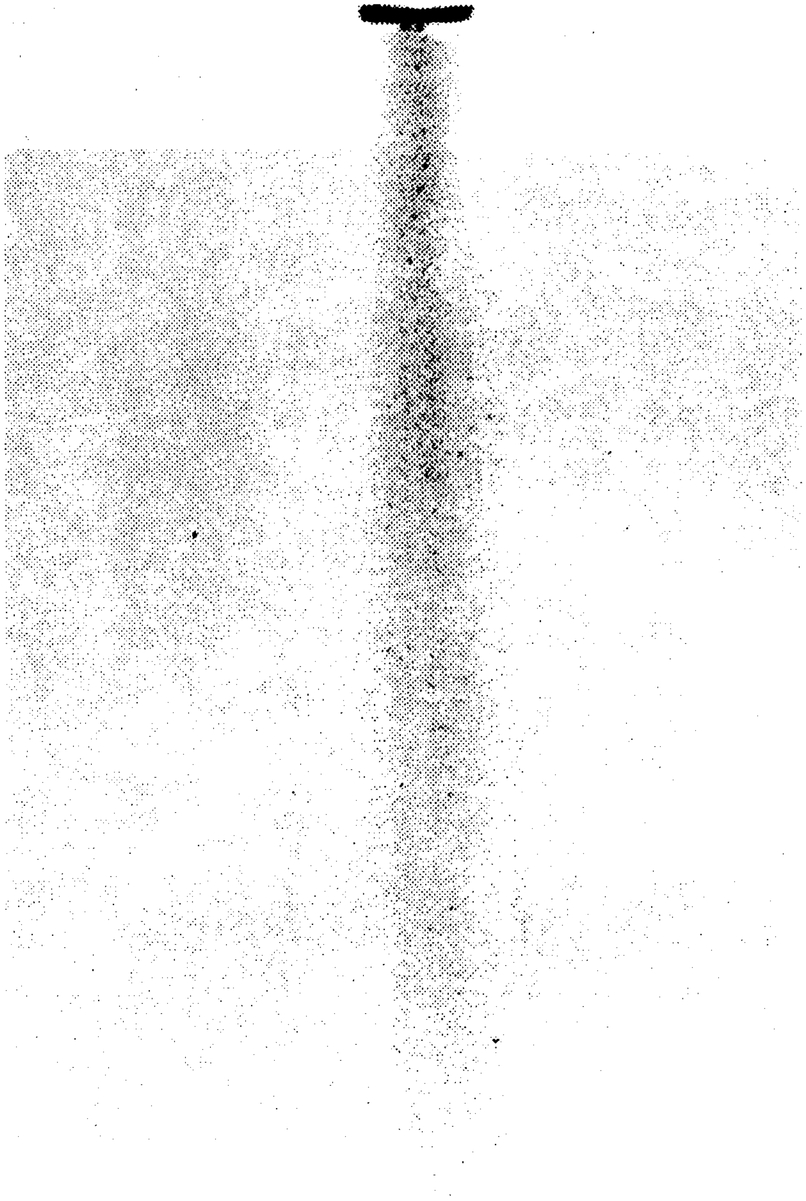

Figure 3. Visualization of (U_p = 20 m/s) particle flow. Mass density of loading is 5%

(a) Original image

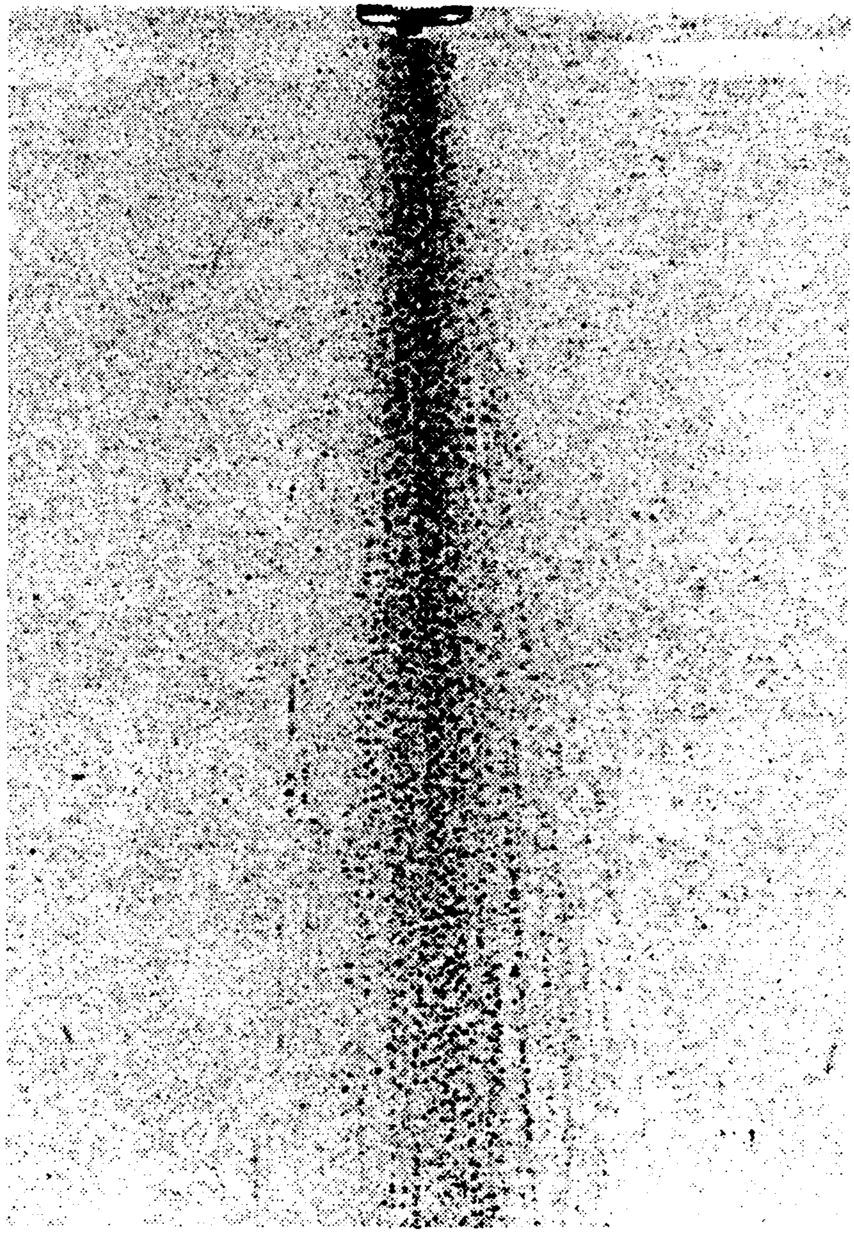

Figure 3. Visualization of (U_p = 20 m/s) particle flow. Mass density of loading is 5%

(b) Filtered image

Figure 4. Visualization of (U_p = 40 m/s) particle flow. Mass density of loading of 2 %

(a) Original image

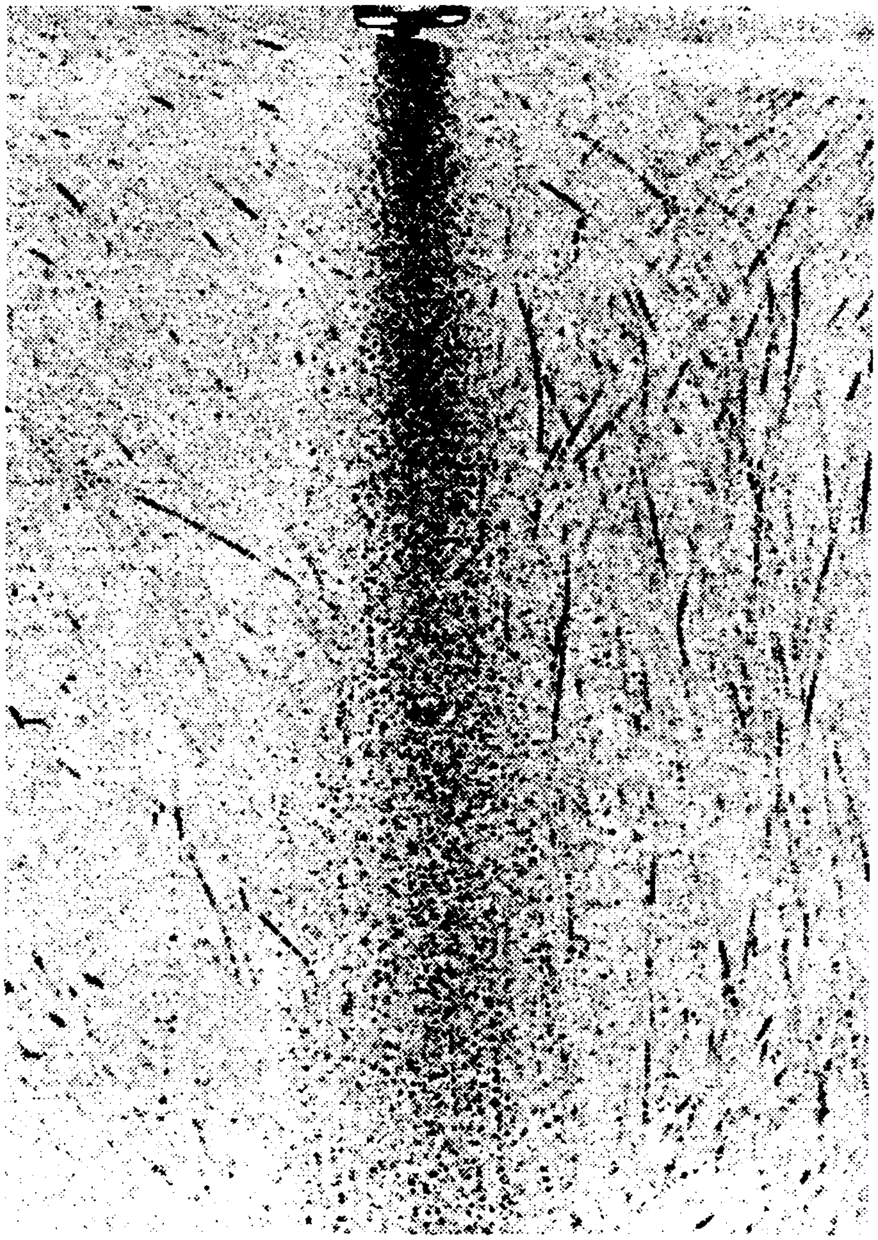

Figure 4. Visualization of (U_p = 40 m/s) particle flow. Mass density of loading of 2 %

(b) Filtered image

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